ON FERRITE LOOP ANTENNA MEASUREMENTS

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Summary

A general discussion relating to the application of small loop antennas with air and ferrite cores is given. A general procedure for simplified testing of ferrite-loaded magnetic-type small antennas is outlined in which radio-frequency radiation performance is expressed in terms of quantities easily measured at audio frequencies. Only a single measurement is needed to characterize the elementary-dipole-type ferrite-loaded antenna. Finally, a number of measurement results are given which apply to the usual rod-type ferrite-loaded loop antenna: measurement parameters cover a broad range of core lengths and diameters. It is found that typical ferrite-loaded loops have little electrical advantage over air loops although the packaging advantage of ferrite loops may be significant.

Introduction

The loop antenna (or magnetic dipole) possesses many features which cause it to be of considerable interest for certain applications. When shielded, the sharp nulls in its pattern have long caused the loop to be favored for direction-finding receiving apparatus. Also of no small importance is its almost complete independence on ground and nearby objects (insofar as circuit tuning is concerned) as long as it is remote from ground to the extent of one or two loop diameters; it is even less critical when electrostatically shielded. Finally, and probably most important of all, is the small physical size of the loop and its ability to be used as the tuned input circuit of a receiver.

The radiation resistance of receiving-type loops is usually very small, typically in the milli- or micro-ohm range. Losses due to loop wire resistance and core magnetic materials make the effective loop resistance literally hundreds of times larger than radiation resistance and hence loops are typically extremely inefficient, losses of 40 db as compared to an efficient resonant antenna not being uncommon.[1]

As receiving antennas up to around 30 megacycles per second, severe antenna losses are not necessarily objectionable. Antenna efficiency is reflected in a correspondingly high receiver noise figure as measured with thermal noise. Below about 30 mcs, atmospheric noise is so much larger than thermal noise that considerable antenna loss can be made up in post-antenna receiver gain (which is relatively cheap) without serious consequence to the practical receiver noise figure.

Relatively small loop antennas of high efficiency are not generally practical for another reason. That is, bandwidth would be so small that signal sidebands could not be received and tuning to the critical degree required might not be possible. For example, if all losses in a typical broadcast loop could be eliminated, then Q would be determined by radiation resistance alone and Q values of the order of hundreds of thousands to millions would result. It is thus a practical necessity that the usual loop antenna be lossy.

In spite of its low efficiency, it remains true that a loop that is well designed and not excessively small can serve as an effective receiving antenna. In view of this, it is somewhat surprising that usage is so limited, particularly in light of the ability of the loop to minimize interference on the basis of direction of arrival.

Above about 30 megacycles per second, thermal noise sets the limit to receiver sensitivity. Then, best receiver operation requires an efficient antenna. Because wavelength is relatively small, there is hardly any point in considering antennas that are very small compared to a wavelength and, as a result, the loop no longer retains so many unique properties. Nevertheless, the loop retains the advantage of being relatively simple and, if the receiver input stage is located at the loop, of avoiding stray losses in transmission line, antenna matching network, and (shielded) receiver input tuned circuit. Further, if the loop diameter is on the order of a tenth wavelength, antenna efficiency can be made to approach 100 percent by making the loop of large diameter conductor, while at the same time, Q values can be made reasonably small.

As contrasted to the use of the loop for receiving, little if any data are available on the small loop as a transmitting antenna. Clearly, for this application, a reasonably efficient antenna with not too large a value of Q is a practical necessity. It should be abvious that the very small loop is not suited to this task. The moderate size loop (about 0.1 wavelength diameter) is, however, eminently suited. The most interesting application is that, when the loop is used as the tank circuit of the final amplifier stage in the transmitter, not only are transmission-line, matching-network, and spurious tuned-circuit losses entirely avoided, but the ever-present problem of antenna tuning and matching is reduced to the simple procedure of tuning the final amplifier stage to resonance.[2] It remains unknown why moderate size loop transmitting antennas have not often been used in this manner.[3]

The advent of high-permeability ferromagnetic ceramics with their small eddy-current and hysteresis losses at radio frequencies has naturally suggested their use as core materials for loop antennas. Currently manufactured broadcast receivers as likely as not contain a ferrite loop antenna.[4-8]

From static considerations, it is evident that a ferrite core tends to gather magnetic flux such that the effective loop area is somewhat larger than the physical area. This enables a loop to be wound with less wire for a given pick-up sensitivity and hence wire losses are reduced, although ferrite losses are introduced (as well as a temperature sensitivity factor). For comparable performance, it appears that the length of the ferrite core must be roughly equal to the diameter of an equivalent air loop. However, other dimensions are smaller; that is, an air loop must be "large" in two dimensions, whereas a ferrite loop need be large in only one. The net result is a packaging advantage for the ferrite loop, somewhat less electrostatic pick-up than that for the air loop, and a structurally simpler device to electrostatically shield, if desired.

The advantage of typical broadcast ferrite loops are not as distinct as might at first be supposed; an air loop with a diameter equal to the length of a typical ferrite rod and wound with large enough wire and with enough turns to give the same inductance can have a radiation resistance and Q about the same as that of the typical ferrite loop, or even larger. When wound with small-diameter wire, the Q of a ferrite loop may be somewhat larger than that of an air loop. Other than for special packaging aspects, it is probable that the current use of the broadcast ferrite loop is more a matter of economics than of performance.

Of course, the specific question arises as to what extent ferrites can make small loops look large not only at broadcast frequencies but up to several megacycles per second (where ferrite losses with high-permeability ferrites tend to become excessive). This is of interest not only in respect to receiving loops, but also to indicate the feasibility for use as transmitting antennas.

Unfortunately, the behavior of a ferrite-cored loop can not be calculated in a reasonable manner except for the special case of an ellipsoidal core, and even then calculations are approximate.[9] Accordingly, an experimental procedure is indicated if any adequate amount of data is to be obtained.

Direct radiation measurements at frequencies below a few megacycles per second are cumbersome to say the least. Each loop must be well balanced, an extensive ground plane is required, and test equipment must be well shielded in order that measurements be consistent and results be significant. In such an environment, data are accumulated at a distressingly slow rate at considerable expense.

It has been found that under certain reasonably lenient restrictions, a static measurement (actually, audio frequency) of the axial magnetic field of a symmetric loop can be used to calculate radiation resistance and radiation intensity in the plane of the loop. The static measuring technique enables reasonably valid data to be accumulated at a rapid rate such that tests of ferrite-cored antennas covering a whole range of parameters can be obtained on a modest budget.

Results of static tests (to be given later and which have been verified in a few specific instances by direct radiation measurements) are not particularly encouraging. For comparable dimensions, ferrite-cored loops do not seem to be more than a few db less lossy than air loops having the same inductance. It should be pointed out that comparison can only be made in terms of inductance because of circuit limitations in specific applications. It is only in the rare case where the operating frequency is always considerably below the natural resonant frequency of the loop that the advantage of ferrite loading is appreciable. A given ferrite antenna may appear to be much better than a given air loop when inductances are quite different; there is nothing to prevent adding turns to the air loop to equalize inductance, in which case the advantage of the ferrite may largely vanish. Nevertheless, ferrites do give a slight advantage in some cases (as well as a packaging advantage) which makes their use for receiving warranted.

The preceding remarks apply mainly to ferrite loops with simple rod-type cores. It might be thought that an advantage of a few db can be gained by using a core that expands in diameter away from the center, that is, a dumbell-type configuration. Any advantage obtained in this manner appears to be slight.

For transmitting, advantages are too small to be significant—neither the small air loop nor the small ferrite loop is practical except in unusual circumstances. For moderate size antennas (compared to a wavelength), a fairly unreasonable bulk of ferrite material is required in order that a significant advantage be given. Above 20 megacycles or so, ferrite losses increase to the extent that ferrite loops may not be as good as air loops; relatively loss-free ferrites at higher frequencies tend to have low permeability and hence the slight advantage obtained with ferrites at low frequencies tends to disappear.

General Measurement Considerations

Any loop antenna small compared to a

wavelength in which loop current is everywhere in phase constitutes a magnetic dipole with dipole moment m. When loop current varies sinusoidally, all the electromagnetic field components about the dipole are proportional to the dipole moment. These fields vary with distance R as k^2/R for the radiation field components, as k/R^2 for the transition field components, and as $1/R^3$ for the induction field components, where $k = 2\pi/\lambda$.[10] Given the wavelength λ, and any one of the three field components, the remaining components may be calculated. Alternately, given dipole moment and frequency, all three field components may be calculated.

At a moderate distance R from the dipole, provided R is large compared to dipole dimensions, and in the static case (that is, in the audio-frequency region), k/R^2 and k^2/R are very small relative to $1/R^3$ and hence can be ignored by comparison. This permits a static measurement of magnetic field intensity to be made in order to find dipole moment. Then radiation at some radio frequency can be determined providing that the dipole moment does not change from static to radio frequencies and providing the dipole is small enough to still be considered an elementary dipole at the radio frequency of interest.

The general measuring philosophy is not changed by adding ferrite loading to the loop, provided the ferrite is of a suitable symmetric form such that the static fields at a moderate distance from the ferrite-loaded dipole are the same as for the elementary dipole.

Secondary effects dependent on the ferrite material can occur when static measurements are used to infer radio-frequency behavior, however. First, the magnetic field may fail to be in phase with the loop dipole current (which in itself is assumed to be everywhere in phase). Second, ferrite permeability may not be the same at audio (static) and radio frequencies. The first effect noted is usually small in most practical instances and as such can be ignored. The second effect may be appreciable but can be accounted for by using a different ferrite material for static tests from that intended for use at radio frequencies such that permeabilities are the same at the two different frequencies of concern. In many practical antennas, radiation characteristics are slowly varying with ferrite permeability and hence the exact value of permeability is not important.

The static measurement technique for small magnetic antennas appears to be more generally applicable than to simple dipole-type structures alone. An imaginary sphere is placed about a small but otherwise arbitrary magnetic antenna. The sphere is assumed to have radius large compared to antenna dimensions. The static tangential magnetic field component is measured over the entire surface of this sphere. It would appear that radiation intensity at a higher frequency is directly proportional to tangential static magnetic field intensity providing that the antenna remains "small" for the radio frequency of interest and that current and magnetic flux time and space distributions within the antenna are the same at both radio and static frequencies.

Many interesting instrumentation techniques come to mind for small magnetic antennas: mechanical sweep devices to automatically display antenna patterns, and electronic integrators to automatically yield total radiation resistance.

It is evident that static measurements must be carried out in a region reasonably free from extraneous magnetic objects, although remarkable toleration in this regard has been experienced.

Since static measurements of magnetic antennas are independent of surrounding nonmagnetic materials, such measurements have the important property that results apply to the ideal free-space antenna. Without unusual counterpoise systems, it is almost impossible to obtain such data from direct measurements in the megacycle range.

Direct radio-frequency measurements usually require that the magnetic dipole antenna be electrostatically shielded; otherwise, incidental electric dipole radiation makes it almost impossible to separate radiation into electric and magnetic types. With static magnetic measurements of a radio-frequency antenna, on the other hand, antenna inductance is so small that no appreciable voltage is required to obtain antenna driving current and hence no significant electric dipole moment exists.

An unshielded magnetic dipole at radio frequencies will radiate to a certain extent as an electric dipole. As a result, radiated power will exceed that calculated for magnetic-dipole radiation alone. Electric dipole radiation typically affects radiation intensity most where the magnetic dipole radiation is a minimum; in the case of the loop, the major effect is to fill in the nulls. Magnetostatic measurements cannot account for electric dipole radiation; hence, magnetostatically predicted radio-frequency radiation resistance may be somewhat less than actual radiation resistance if the magnetic-type antenna is unshielded.

Special Measurements for the Elementary Dipole

If by symmetry and other arguments it is known that the static fields about the small magnetic antenna at a distance large compared to antenna dimensions follows the familiar "figure-8" pattern applicable to the elementary magnetic dipole, then a simplified magnetostatic measuring technique is applicable. This will occur, for example, with typical ferrite loop antennas.

In this case, only a single magnetic field measurement is required; from it, the remaining portions of the field pattern follow immediately. In fact, it is not necessary to measure a quantity directly related to radiation intensity such as tangential magnetic field at all; rather a uniquely defined radial component of magnetic field is adequate.

The most convenient measurement is that of the radial component of magnetic field in the axial direction of the dipole under test, which is the null direction of the figure-8 radiation pattern. Coaxial with the antenna under test and at a distance large compared to antenna dimensions is placed a small pick-up coil. The antenna coil is driven with an audio sine wave. An alternating-current voltmeter across the pick-up coil measures pick-up voltage. Pick-up voltage is directly proportional to axial magnetic field intensity (which in turn is proportional to maximum dipole radiation intensity at radio frequencies) providing the diameter of the pick-up coil is small so that magnetic field intensity over the pick-up loop is constant.[11]

After making a voltage pick-up measurement for the dipole under test, a second pick-up voltage measurement is made with an air loop of known dimensions substituted for the test dipole. Since the axial magnetic field, dipole moment, and radiation properties of the air loop are known theoretically to good accuracy, this simple comparison test directly evaluates arbitrary dipoles in terms of an equivalent air loop.

The field intensity along the axis of a circular loop in air of n concentrated turns and radius a carrying current I_0 at a distance z from the center of the loop is

$$H_z = \frac{nI_0a^2}{2(a^2 + z^2)^{3/2}} \cong \frac{nI_0a^2}{2z^3} \tag{1}$$

where units are in the usual MKS system and where the approximation applies for $z \gg a$.[12]

Radiation resistance for the loop in free space is

$$R_r = 20\pi^2 n^2 (2\pi a/\lambda)^4 \tag{2}$$

where λ is wavelength.[13] It is to be noted that (1) and (2) are reasonably valid even at frequencies where loop diameter is on the order of $\lambda/10$, providing loop current is everywhere in phase. Hence the test procedure outlined here is fairly accurate even for antennas that are not "very" small.

Combining the approximation of (1) with (2), there results

$$R_r = 80\pi^2 (2\pi/\lambda)^4 \left(\frac{z^3 H_z}{I_0}\right)^2, \quad z \gg a \tag{3}$$

which does not contain either loop radius or number of turns. For a given z (which is specified by the experimental set up), and for arbitrary λ, the only parameter of importance is the <u>axial magnetic field per unit antenna current.</u> In terms of H_z/I_0, it is evident that an arbitrary dipole-type antenna has an equivalent air loop antenna with radius and number of turns given by

$$na^2 = 2z^3 (H_z/I_0), \quad z \gg a \tag{4}$$

Calibration of the test apparatus is made with an air loop in which n, a, z, and I_0 are known. This gives the proportionality constant between magnetic field and measured pick-up voltage, or if preferred, the relation between measured voltage and H_z/I_0. An arbitrary dipole-type antenna can then be tested and, for air-loop and test-loop currents the same, pick-up voltage for the test loop relative to that for the standard air loop gives the equivalent na^2 for the test loop relative to the actual na^2 for the loop under test.

In addition to its worth as a testing procedure <u>per se</u>, reducing relative antenna performance to the simple ratio H_z/I_0 aids considerably in design thinking: ferrite core configurations for maximizing H_z/I_0 at a given distance z from the antenna are more easily understood than concepts related to the general boundary-value problem.

<u>Selected Experimental Results</u>

Three different tests, covering relevant parameters in each case, were made by static methods. In the first test, radiation resistance as a function of ferrite cross-sectional area for fixed ferrite rod length and for various numbers of loop turns of different winding lengths, was determined. In this, the coil was wound around one up to five 8-inch long, 3/8 inch diameter ferrite rods bundled together.[14]

In the second test, coils with various numbers of turns were wound along the entire length of a 3/8-inch ferrite rod for rod lengths of 4 to 24 inches.

The third test, which was almost an afterthought, consisted of placing one or more ferrite rods (8 x 3/8) inside a 30-centimeter (diameter) 4-turn air loop with rod and loop axes parallel.

Static measurements were made by placing the loop under test and a signal pick-up loop coaxially at a center-to-center distance of 1.25 meters. The test loop was driven at 3 kcs with 0.15 ampere (rms) current. The voltage from the (resonant) pick-up loop was read with a sensitive AC voltmeter. The voltage is thus proportional to axial magnetic field. The entire apparatus was calibrated with a 4-turn (concentrated) 30-cm (diameter) air loop which gave a pick-up voltage of 0.054 volt (and inductance of 14 microhenrys). Since the axial magnetic field of the air loop can be accurately calculated, the single calibration measurement suffices to give quantitative results for all subsequent tests.

Radiation resistance is in all cases proportional to the square of the pick-up voltage. For example, the air loop at 8.5 mcs has radiation resistance of 0.0016 ohm.

Results for the first test are shown in Figs. 1 and 2. The parameter is number of turns N. Figure 1 applies to close-wound coils and Fig. 2 to a moderately distributed winding. The solid curves apply to pick-up voltage and the dashed curves to inductance. Arrows along the ordinants of Figs. 1-3 refer to pick-up voltage e and inductance L of the reference air loop.

Clearly, pick-up voltage and hence radiation resistance increases with ferrite cross-sectional area. The discouraging aspect is that inductance also increases. Consider Fig. 2. If one rod with 30-turns is compared with 5 rods, the number of turns on the 5 rods must be reduced to an estimated 15-turns for the same inductance. The resulting pick-up voltage is about doubled (or radiation resistance about quadrupled) but at the cost of a five-fold increase in ferrite material. A rule of thumb would seem to be that radiation resistance is roughly proportional to ferrite core area for constant ferrite core length and coil inductance. In the air loop, radiation resistance increases as the square of area. This seems to imply that it is only for quite small loops that ferrite cores provide a significant advantage.

The results of the second test where 3/8-inch rod length is the parameter and the winding is distributed over the entire core is shown in Fig. 3. (The points for zero rod length were calculated from the air-loop formula.) It is to be noted that the 20-turn ferrite loop, 24 inches long, has about the same inductance as the standard air loop (which has a diameter of only 12 inches) but has only about half as great a radiation resistance. Increasing ferrite length in general allows the winding to be distributed to a greater extent which reduces its inductance. It would appear that length beyond a certain value is not important; perhaps a length-to-diameter ratio up to roughly 30 is useful. For a given volume of ferrite, it is better to increase cross section than length.

Curves comparable to Fig. 3 for concentrated windings have inductance and pick-up slightly larger than those of Fig. 1 for the single rod except for short lengths where values decrease. As a function of rod length and for constant inductance, it would appear that pick-up voltage rises rapidly with rod length for small lengths and eventually becomes relatively constant.

The third test consisted of placing 8 x 3/8 inch rods at various places inside the reference air loop (4-turns, 30-cm diameter). A single rod in the center increases pick-up voltage by about five percent. When the rods are placed near the coil, pick-up is increased somewhat more. Figure 4 shows the test results. With 5 rods, loop radiation resistance is increased by a factor of only 1.77 (and loop inductance increases as well). The same increase can be obtained with the air loop by increasing the diameter a mere fifteen percent; in this case, the modified air loop is actually less bulky than the original loop with five ferrite rods for loading. Roughly, pick-up voltage increases linearly from the value applicable to the air loop proportionally to the number of rods placed inside and along the periphery of the loop, although considerable ferrite bulk is required for a significant increase.

It was felt that loop performance might be improved by having a dumbell-shape core with the winding placed in the constricted region. Accordingly, a ferrite rod was formed into a suitable shape by affixing small pieces of ferrite at appropriate places. Performance results were not found to be significantly better than for the simple rod core; a study of the magnetic flux distribution tends to justify these negative results.

Conclusion

A static measuring method has been described which makes the evaluation of small ferrite-loaded antennas simple and meaningful. Results using the technique for ferrite-cored loops of various lengths and diameters do not show electrical behavior much better than that obtainable with air loops of similar dimensions. The basic limitation is that inductance of ferrite-loaded antennas increases correspondingly with the increase in effective loop diameter for a given number of loop turns: for constant inductance, the number of loop turns must be reduced as the amount of ferrite loading increases.

Although the addition of ferrite loading to small loop antennas does not greatly improve radiation efficiencies, there does remain, however, the interesting possibility for realizing small directive antennas with ferrite-loaded structures physically different from the simple dipole.

Acknowledgement

The work reported here was made possible through interest expressed by Hycon Manufacturing Company, Pasadena, California, Military

Electronics Division. Mr. Mih Yin constructed the equipment and performed the measurements.

References and Footnotes

1. H.A. Wheeler, "Fundamental Limitations of Small Antennas," Proc. IRE, March, 1947, pages 1479-1484. (Air core loops alone are treated).

2. Any inductive antenna can be used in this manner by adjusting antenna input inductance to resonate with tube and tuning capacitance.

3. Radiation of harmonics can be avoided with traps and/or a low pass filter in series with the loop.

4. C.A. Grimmett, "Ferrite-Cored Antenna," IRE National Convention Record, Part 7, 1954. Also see Proc. IRE (Australia), Vol. 16, Feb., 1955.

5. W.A. Everden, "Ferrite Rod Aerials," Wireless World, Part 2, 1954, page 440.

6. J.S. Belrose, "Ferromagnetic Loop Aerials," Wireless Engineer, Feb., 1955.

7. R.E. Burgess, "Iron-Cored Loop Receiving Aerial," Wireless Engineer, Vol. 23, June 1946.

8. W.H. Rumsay and W.L. Weeks, "Electrically Small, Ferrite-Loaded Antennas," 1956 IRE Convention Record, Part 1, pages 165-170.

9. Rumsay and Weeks, Loc. Cit.

10. Electromagnetic Theory, J.A. Stratton, McGraw-Hill Book Company, New York, 1941, pp. 430-438.

11. The primary of an automobile ignition coil with its straight laminated core makes a convenient pick-up coil which is fairly selective and resonant with its own stray capacitance (and the open secondary coil) at about 3 kilocycles.

12. Fields and Waves in Modern Radio, 2nd Ed., S. Ramo and J.R. Whinnery, John Wiley and Sons, New York, 1953.

13. Antennas, J.D. Kraus, McGraw-Hill Book Co., New York, 1950.

14. Ferrite material in all tests was General Ceramic type Q. This type of ferrite can readily be obtained from jobbers in the form of a ready-made loop antenna, for example, from a Miller transistor antenna for broadcast receivers.

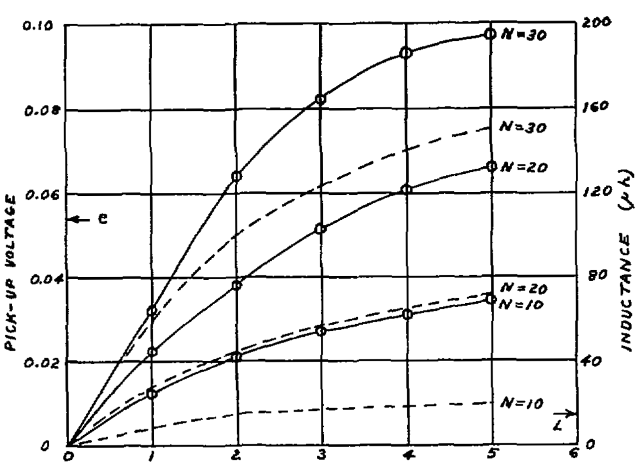

Fig. 1
Pick-up (solid) and inductance (dashed) as functions of the number of bundled 8" x 3/8" rods. Winding centered on rods with length 3/8", 3/4", and 9/8" for N = 10, 20, and 30 respectively.

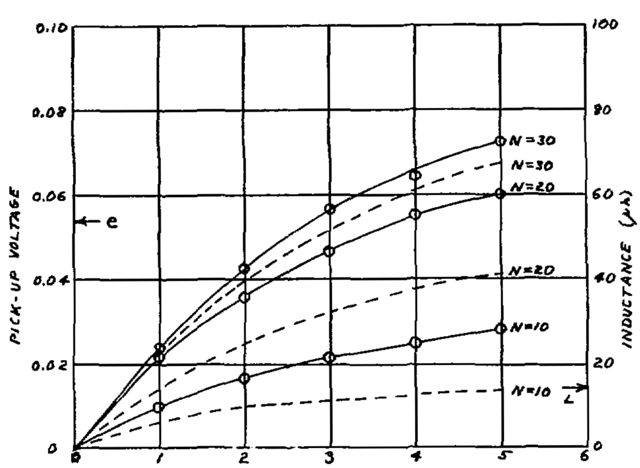

Fig. 2
Pick-up (solid) and inductance (dashed) as functions of the number of bundled 8" x 3/8" rods. Winding centered on rods with length 2-1/2", 5", and 7-1/2" for N = 10, 20, 30 respectively.

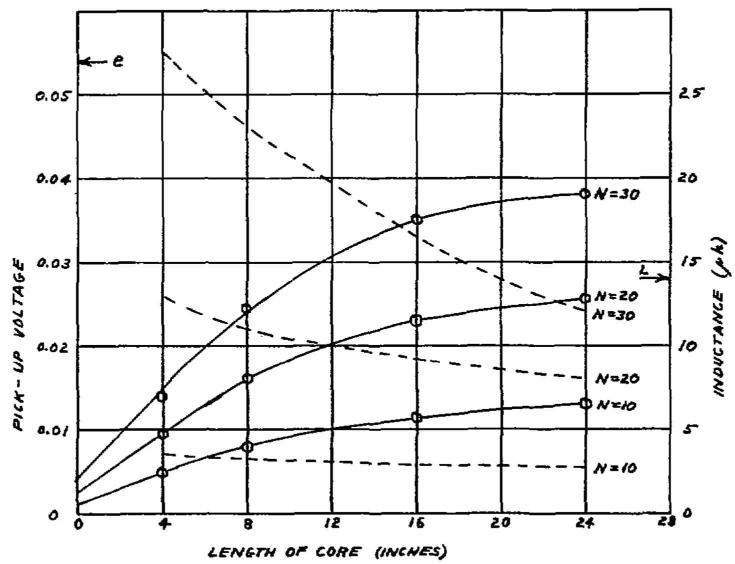

Fig. 3
Pick-up (solid) and inductance (dashed) of a single 3/8" rod with distributed winding as functions of rod length for N = 10, 20, and 30.

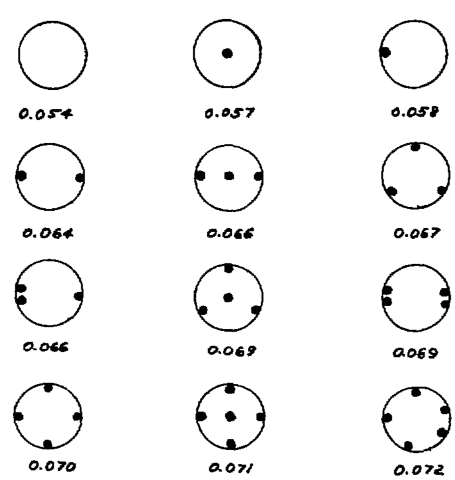

Fig. 4
Pick-up as a function of number and placement of 8" x 3/8" rods within a 4-turn, 30-cm air loop.